

What Makes the Crab Pulsar Shine?

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Abstract. Our high time resolution observations of individual pulses from the Crab pulsar show that the main pulse and interpulse differ in temporal behavior, spectral behavior, polarization and dispersion. The main pulse properties are consistent with one current model of pulsar radio emission, namely, soliton collapse in strong plasma turbulence. The high-frequency interpulse is quite another story. Its dynamic spectrum cannot easily be explained by any current emission model; its excess dispersion must come from propagation through the star's magnetosphere. We suspect the high-frequency interpulse does not follow the "standard model", but rather comes from some unexpected region within the star's magnetosphere. Similar observations of other pulsars will reveal whether the radio emission mechanisms operating in the Crab pulsar are unique to that star, or can be identified in the general population.

Keywords: pulsar emission mechanism, Crab pulsar

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How do pulsars make radio emission? What are the physical conditions in the magnetosphere that make the pulsar "shine" in the radio? Is there one answer to this question, or many? What observable quantities can identify the emission mechanism, or distinguish between different theories of the emission mechanism? In order to answer these questions, we have developed specialized data acquisition systems and used them to observe individual radio pulses at the highest possible time resolution. Our goal is to find ways to use our data to confront competing theories of pulsar radio emission.

Up to now we have concentrated on the Crab pulsar, because it occasionally emits very bright pulses which are ideally suited to our data acquisition systems. The mean profile of the Crab pulsar is dominated by a Main Pulse (MP) and an Interpulse (IP), which can be identified from low radio frequencies (below ~ 100 MHz) up to optical, X-ray and γ -ray bands (*e.g.*, [1]). The similarity of the mean profile across this broad frequency range suggests that both radio and high-energy emission come from the same regions in the magnetosphere.

In traditional pulsar models, the MP and the IP are thought to come from plasma, at relatively low altitudes, moving out along open field lines from the star's two magnetic poles. Other geometrical models have been also been suggested, such as emission from higher-altitude "outer gaps" or "caustics" [2, 3] above each magnetic pole, or broad outflows over one magnetic pole [4]. While these models differ in geometry, they all agree that physical conditions should be similar in the regions which emit the MP and IP. Because similar physics should lead to similar emission processes, these models suggest that the MP and IP should be the same in their observable quantities (such as spectrum, time signature, or dispersion). We were — and remain — quite surprised

that this turns out *not* to be the case in the Crab pulsar.

In this paper we compare and contrast properties of the MP and IP, and consider what our results tell us about pulsar radio emission physics. We illustrate our discussion with two example pulses, in Figures 1 and 2; more details and examples can be found in [5] and [6].

OUR OBSERVATIONS

Between 1994 and 2002 our group observed strong pulses from the Crab pulsar between 1 and 5 GHz at the VLA and Arecibo. Our Arecibo observations were designed with 2-ns time resolution, in order to test competing models of the radio emission mechanism. We initially concentrated on the MP, because it is stronger than the IP below ~ 5 GHz in the star's mean profile, and also because giant pulses are more common at the phase of the MP at these frequencies [7]. Our results, and our data acquisition system, are described in [5].

To follow up on these results, we extended our data acquisition system to higher time resolution. We went to higher frequencies (5 to 10 GHz) in order to take advantage of the 2.2-GHz bandwidths (and corresponding sub-ns time resolution) available at Arecibo. We recorded individual IPs as well as MPs, because at these frequencies strong pulses are much more common at the phase of the IP [7]. These new observations, carried out between 2003 and 2006, are reported in [6]. We were astonished to find that IPs are very different from MPs at these frequencies. The IP differs from the MP in polarization, time signature, spectrum and dispersion, as discussed below.

All of our IP observations were taken between 5 and 10 GHz. Technical limitations, as well as the scarcity of strong IPs at lower frequencies, kept us from observing

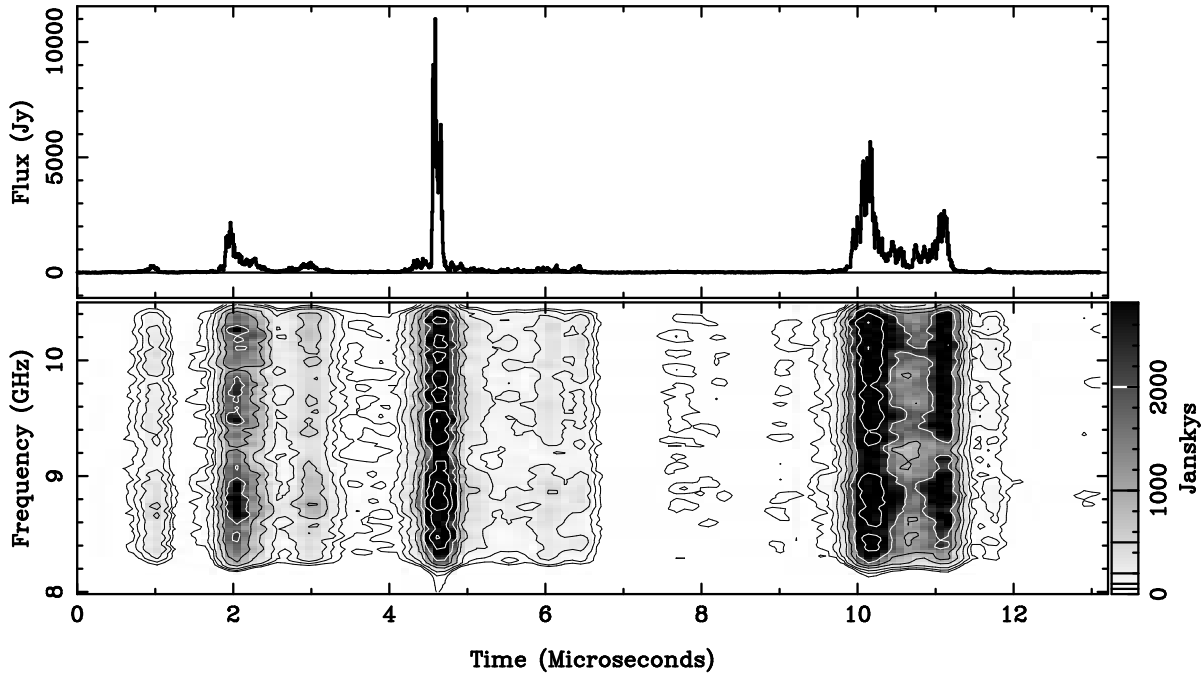


FIGURE 1. An example of a Main Pulse, observed with 2.2-GHz bandwidth at 9 GHz, and coherently dedispersed [5]. The pulse seen in total intensity (upper panel, plotted with total intensity time resolution 6.4 ns) contains several short-lived microbursts. The dynamic spectrum (lower panel, plotted with resolution 102 ns and 19.5 MHz) shows that the microburst emission spans the full receiver bandwidth. In a few MPs individual, short-lived nanoshots are sparse enough in time to be separately identified (shown in [5, 6]); these examples reveal the dynamic spectrum of the nanoshots is relatively narrow.

the IP below 4 GHz. We are therefore describing the “high-frequency IP”, which occurs at a slightly earlier rotation phase from the “regular” IP (as seen at lower radio frequencies as well as in high-energy bands; *e.g.*, [1]). This phase offset suggests that the high-frequency IP may not be related at all to the regular IP; it may come from a very different part of the magnetosphere.

DIFFERENT TIME SIGNATURES

Most MPs contain several short-lived microbursts, as illustrated in Figure 1. At 1.4 GHz the microbursts are typically $\sim 3\text{--}30\ \mu\text{s}$ long, with some tendency for more powerful bursts to be shorter-lived [8]. At this frequency the microbursts have a fast-rise, slow-decay shape. Below ~ 1 GHz, the pulse width is determined by interstellar scattering. At higher frequencies, however, the burst width is larger than ν^{-4} extrapolation predicts [9], and the burst width can change by more than a factor of ten from burst to burst [8]. Thus, the microburst width above ~ 1 GHz is not due to interstellar effects; we are observing the temporal profile of the burst as it leaves the star.

At higher frequencies, the microbursts are shorter; their width scales approximately $\propto \nu^{-2}$ [9]. They lose their fast-rise, slow-decay profile, and become more symmetric in time, as illustrated in Figure 1.

An occasional MP can be resolved into well-separated, short-lived “nanoshots”. In [5] we reported 5-GHz nanoshots shorter than 2 ns; in our later work [6] we found similar nanoshots at 7 and 9 GHz, some of which remain unresolved at 0.4 ns. We suspect that all MP microbursts are “clouds” of overlapping nanoshots; only rarely are the nanoshots sparse enough to be identified individually.

IP emission is more continuous in time than MP emission. It usually begins with a rapid onset, followed by slower decay, as seen in Figure 2. Although a second burst can often be identified, overlapping in time with the first burst, IP emission is not broken up into the short-lived microbursts that characterize the MP. The IP lasts $\sim 1\text{--}3\ \mu\text{s}$ at 9 GHz (as measured by the equivalent width of the autocorrelation function), and somewhat longer at lower frequencies, approximately consistent with the ν^{-2} behavior of MP microbursts.

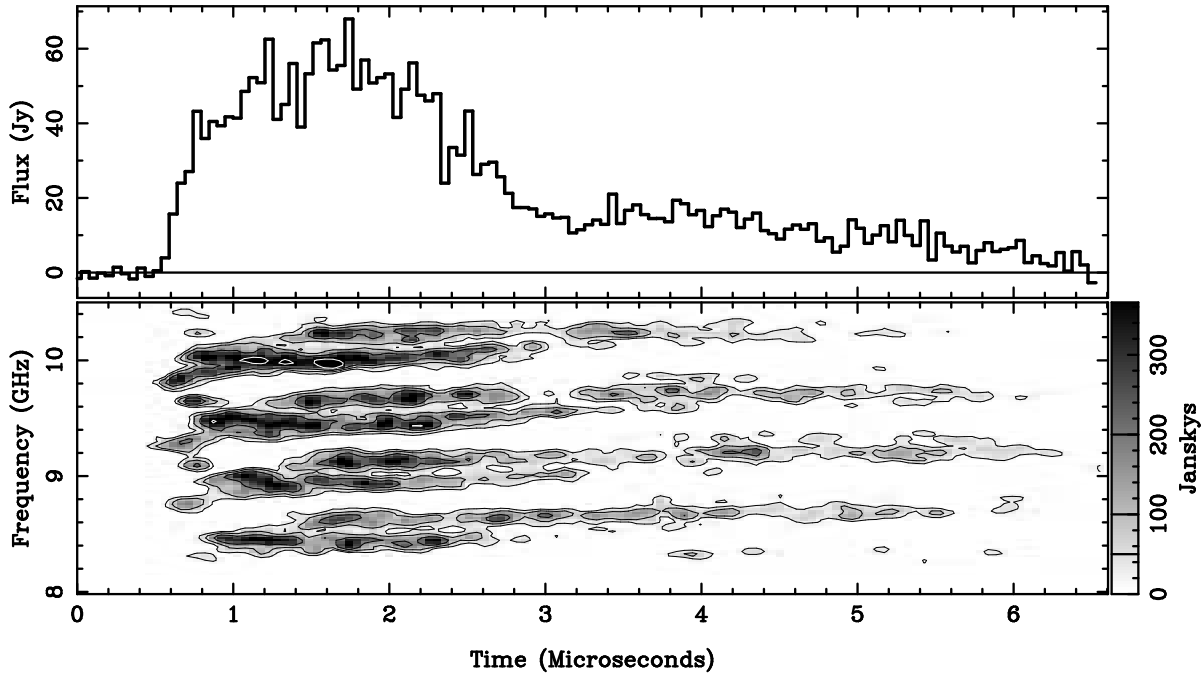


FIGURE 2. An example of an Interpulse, observed with 2.2 GHz bandwidth at 9 GHz, and coherently dedispersed. The IP seen in total intensity (upper panel) typically contains 1 or 2 sub-bursts; thus it has a simpler time signature than the MP (as in the example of Figure 1). The regular *emission bands* in the dynamic spectrum (lower panel) are not due to instrumental or interstellar effects, but are characteristic to the emission physics of the IP. Note that the secondary burst, seen in total intensity, coincides with the appearance of new band sets in the dynamic spectrum. Plotted with total intensity time resolution 51.2 ns, and dynamic spectrum resolution 104 ns and 19.5 MHz.

DIFFERENT SPECTRAL SIGNATURES

MP microbursts tend to be broadband, emitting across our full 2.5-GHz bandwidth, as Figure 1 illustrates. The emission is sometimes, but not always, weaker towards the high end of the band; this is probably consistent with the known steep spectrum of the Crab pulsar. However, when we captured individual (sparse) nanoshots between 6 and 10 GHz, we found that their spectra are relatively narrow-band, $\delta\nu/\nu \sim 0.1 - 0.2$ [6]. If all MP microbursts are indeed collections of nanoshots, then their broad-band spectrum does not reflect the fundamental emission process, but comes from a composite of overlapping nanoshots. The steep radio spectrum of the MP is due either to nanoshots at higher frequencies being fewer, or fainter (or both).

The dynamic spectrum of the IP is dramatically different. As Figure 2 illustrates, the IP spectrum contains regular *emission bands*, which we have detected from 5 to 10 GHz. All the bands within one set turn on at the same time (to within $\sim 100 \mu\text{s}$). A single IP usually contains more than one band set; additional sets turn on ~ 1 -2 ns later in the pulse, often shifted to a slightly higher fre-

quency. Band sets which start later in a given IP can often be identified with a new “burst” in the total intensity profile. The center frequency of each band in a band set usually remains constant, but sometimes drifts slightly upwards during the few- μs lifetime of the band set.

Although at first glance the bands appear regularly spaced, in reality they are *proportionately spaced*: the frequency separation between two adjacent bands is 6% of their mean frequency. We have never seen band sets that do not span our full observed bandwidth (2.2 GHz); we therefore suspect the bands extend from 5 to at least 10.5 GHz in a single IP. Because the high-frequency IP does not continue below ~ 4 GHz in the mean profile, we speculate that the emission bands we observe do not continue below that frequency.

DIFFERENT POLARIZATION

The mean-profile MP is weakly polarized at 1.4 and 5 GHz (typically 20%; [10]). Individual nanoshots in a single MP, however, can be strongly polarized, but the sense of the polarization can vary from one nanoshot to

the next [5]. This tells us that the intrinsic MP emission process is highly polarized, but no local “memory” in the emission region retains the sense of polarization from one nanoshot to the next.

Once again the IP behaves differently. It is strongly linearly polarized (at least 50%) at 5 and 8 GHz in the mean profile [10]. Thus, the intrinsic IP emission process is highly polarized, and some local “memory” here does retain the sense of polarization from one IP to the next.

TWO TYPES OF RADIO EMISSION

The dramatic temporal, spectral and polarization differences between the MP and IP point to the existence of two quite different mechanisms for coherent radio emission operating in this star.

The time and spectral signatures of the MP appear to be consistent with existing models of pulsar radio emission. In [5] we compared time signature predictions of three classes of radio emission mechanisms then in the literature: coherent charge bunches, stimulated emission/masers, and soliton collapse in strong plasma turbulence. We argued that only one of these three — soliton collapse, as modelled numerically by [11] — has a characteristic time which is short enough to be consistent with the nanoshots we observed at 5 GHz. The narrow-band nature of individual nanoshots, which we found in [6], is also consistent with [11]. We therefore propose that the individual, short-lived nanoshots which comprise MP emission are produced by soliton collapse in strong plasma turbulence.

The unusual dynamic spectrum of the IP suggests that it involves quite different emission physics from MP emission, and probably requires some new thinking. We are not aware of any models of pulsar radio emission which predict such regular emission bands over such a broad frequency range. In particular, plasma resonant emission — which has been a popular model for pulsar radio emission — tends to be narrow-band, centered on a frequency determined by plasma density and/or magnetic field in the emission region.

As a naive example, if this were coherent plasma emission, the IP emission region would have to be unusually stratified, containing 15 density steps, each 3% higher than its neighbor, in order to produce the proportionately spaced emission bands we see between from 5 to 10 GHz. In order to turn on within 100 ns of each other, these stratifications would have to be co-located to within 30 m. We find such structures unlikely. Alternatively, the IP emission might come from a high-altitude cyclotron resonance, as suggested by [12]. Again, stringent relations between the plasma density, particle energy and viewing angle are required in order to reproduce the full range of proportional band spacing; it is not clear that

such conditions will arise naturally in the star’s magnetosphere.

In [6] we speculated that the bands may be an interference phenomenon. We tend to like this idea, but emphasize that many details must be worked out before this speculation can be described as a “model”. In particular, we need an intrinsically broad-band emission mechanism (such as a double layer), which coexists with regular, small-scale plasma structures (to provide the interference). How to make and maintain such structures is far from obvious.

HIGHER INTERPULSE DISPERSION

The IP is more dispersed than the MP. The dispersion of individual MPs does not vary significantly from pulse to pulse (to less than $\sim .001\text{pc-cm}^{-3}$), and is approximately consistent with the monthly values monitored at Jodrell Bank (based on mean profiles at lower frequency: [13]). The dispersion of individual IPs, however, varies substantially from pulse to pulse during a single run, by $\sim .01\text{pc-cm}^{-3}$. On average IPs are more dispersed than MPs by about this same amount. Our methods and results regarding MP/IP dispersion will be reported in [14].

Although pulsar dispersion is traditionally assumed to be due to the signal’s passage through the interstellar medium (ISM), this picture cannot explain why IPs have higher dispersion than MPs observed a few minutes later. It follows that the IP signal must gain the extra dispersion *during its passage through the star’s magnetosphere*; the extra dispersion induced by that passage can vary significantly within a few minutes. Our data also suggest that the IP dispersion law has a flatter frequency dependence than the standard cold-plasma dispersion law which describes ISM dispersion — but further observations are needed to confirm this result.

SUMMARY: THE CRAB PULSAR

We have identified two different types of coherent radio emission from the Crab pulsar, one associated with the MP, the other associated with the high-frequency IP. Two different radiation mechanisms seem to be operating within the star’s magnetosphere. In addition, the higher dispersion of the high-frequency IP suggests the signal has passed through an unusually large plasma column before leaving the pulsar.

Conventional wisdom ascribes the MP to emission from the open field line region above one of the star’s magnetic axes. If this is the case, the high-frequency IP is probably not simply radiation from the other magnetic pole. It is more likely to come from some unexpected part of the magnetosphere; its phase offset, relative to

the regular IP [1], corroborates this idea. The suggestion from [12] that the high-frequency IP is emitted within the closed field line region may be on the right track.

WHAT ABOUT OTHER PULSARS?

Our results apply to strong pulses from the Crab pulsar; do they have any relevance to other pulsars? Is the Crab pulsar a useful example of pulsar radio emission physics?

Some might argue that the Crab pulsar is so unusual that our results should not be applied to other stars. It is, of course, possible to argue that the high-flux “giant” pulses which we capture are not typical of more common “weak” pulses which are usually recorded from this star [15] (although the observational issues are not yet resolved; *e.g.*, [16]). It is also true, of course, that in many ways the Crab pulsar is not typical of the general pulsar population. It is a young pulsar, with unusually strong high-energy pulsed emission. Its mean profile is unusual in both the number and phase location of emission components, and its unusual polarization sweep [10]. It shows more “giant” pulses than most pulsars do (although new work on intermittent pulsars suggests pulsar duty cycles are not yet understood *e.g.*, [17]).

We nonetheless think our results are broadly applicable. The phenomenon that make the Crab pulsar unusual are *macroscopic*, in that they depend on dynamics of the magnetospheric plasma. On the other hand, coherent radio emission is a *microscopic* process. Plasma dynamics provide a source of free energy; if plasma conditions are favorable, locally coherent charge motions in the plasma convert that free energy to intense radio emission. More than one macroscopic situation can lead to the same microscopic physics, and thus the same radio emission.

As a concrete example, we know beam instabilities can drive the strong plasma turbulence which we believe is responsible for coherent radio emission from the MP. Beams may come from relative streaming of electrons and positrons in an imperfectly shielded electric field, for instance in the open field line region close to the star’s magnetic poles (as in the traditional view of pulsars). Alternatively, we know that local reconnection events can drive beams (as happens in solar flares). In pulsars such events may be driven by high-altitude plasma shear in the dynamic upper magnetosphere (*e.g.*, [18, 19]). The observable properties of coherent radio emission from both scenarios could be very much the same.

We therefore argue that our results on the Crab pulsar may well be relevant to other pulsars; but this speculation must be backed up by observations. The next step, therefore, is to look at other pulsars with similar time and frequency resolution. To do this will require the sensitivity of the largest radio telescopes and the widest practical bandwidths.

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